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Time to Integrate Pollinator Science into Soybean Production

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Soybeans cover 129 million hectares globally. Soybean productivity can increase with pollinator management, but soybean cultivation practices commonly ignore biotic pollination. If pollinator habitats are created within soybean landscapes and policies to limit agricultural expansion are implemented, millions of hectares could be restored for biodiversity without loss of soybean production.

Soybean Productivity Increases with Biotic Pollination

Soybeans (*Glycine max*) are a globally important crop (<http://www.fao.org/faostat/en/#home>) with multiple uses (food, fodder, oil, and industrial). Their expanded cultivation is also one of the main drivers of global biodiversity loss [1,2]. Soybeans have replaced natural forests, savannahs, and grasslands as well as other crops (including grains, legumes, hay, and perennial pastures), reducing landscape and crop diversity. Soybean monocultures increasingly dominate agricultural landscapes, with the area of cultivation expanding by more than 900% since the 1960s in North and South America (<http://www.fao.org/faostat/en/#home>). There is another way, however, to maintain or increase global soybean production without further loss of crop diversity and native habitats.

Decades of research now indicate that soybean productivity can be increased through pollinator management (Figure 1). Most commonly, studies have compared two biotic pollination scenarios: open versus enclosure (i.e., no pollinators) treatments. In many studies the ‘open’ treatment was associated with the enhancement of biotic pollination, such as the addition of honey bee (*Apis mellifera*) hives or habitat enhancement for wild pollinators (see Table S1 in the supplemental information online). Other common types of studies compared enclosures with honey bee hives inside (the enhanced biotic pollination scenario) with enclosures without honey bee hives (the no pollinator scenario). Pooling together all types of contrasts, increases in crop yield (a measure of soybean productivity expressed in kilograms of seeds per m²) due to improved biotic pollination (‘pollinator dependence’) were observed in 15 of 23 contrasts. The remaining eight contrasts showed no significant differences (Table S1). Such increases were mostly related to improved pod set (number of pods per plant) and (or) seed set (number of seeds per pod) with small changes in individual seed weight. Specifically, pod set increased with improved biotic pollination in 12 of 14 contrasts, seed set increased in 12 of 17 contrasts, while individual seed weight increased in only two of 18 contrasts (Table S1). Some of the studies showing no significant differences had low numbers of replicates (and thus little ability to detect differences; Table S1) or experimental problems (e.g., the enclosures were established late in the flowering season). We included these studies in our analysis nonetheless, as our primary aim here is to demonstrate the growth in the scientific knowledge on soybean biotic pollination during the past decades and discuss its implications.

The magnitude of yield increases observed with improved biotic pollination are high. Crop yield, pod set, and seed

set increased 0–126%, 0–91%, and 0–249%, respectively (Table S1). The mean increase across the 23 contrasts for crop yield was 21% (this is a conservative figure as we assumed that yield increase was zero for those contrasts without significant results). Putting these values into context, soybean yield increases due to other genetic and management factors (such as increased agrochemical use) during 2010–2019 for Brazil, USA, and Argentina were only 8%, 9%, and 15%, respectively (<http://www.fao.org/faostat/en/#home>).

These results are pooled from studies in different regions with contrasting soybean varieties, which suggests high consistency in the positive impacts of pollinators. The varieties assessed correspond to their common use by farmers and include popular state-developed and privately developed seeds designed for high performance in each region (Table S1). Thirteen of the 16 studies were performed in the globally most important soybean-producing countries, namely Argentina, Brazil, and USA (Table S1). However, given the large and highly dynamic industry of soybean seed development, more pollination studies across a wide and systematically selected set of soybean varieties are needed around the world, especially in unrepresented countries, such as China and India where soybean production is a major economic component. Also, new studies should extend the assessment of pollinators (and their flower visitation rate) to the center and most isolated parts of large soybean fields to estimate spatial variability in their abundance and diversity of flower visitors and fully evaluate the need and potential for improvements.

While soybeans are to a great extent self-pollinating, this mechanism renders a high percentage of aborted flowers [3]. Positive effects of pollinators on soybean pod set and seed set may be due to the male-sterile characteristics of flowers located distally on the primary raceme or



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Figure 1. Soybeans Need Pollinators and Their Habitats. Soybeans are typically produced in large monocultural fields (A), which have replaced native habitats as well as other types of cropland and pastureland. Integrating pollinator management into soybean production could improve productivity through pollination by wild pollinators, such as bumble bees (B), and managed pollinators, such as honey bees. Taking advantage of the production benefits of pollinators requires the conservation and restoration of native habitats, such as floral strips (C). Photo credits: Omar de Kok-Mercado, Iowa State University (A,C) and Adam Varenhorst, South Dakota State University (B).

on the secondary racemes of some soybean varieties [4]. Such flowers would require pollen transfer by pollinators for fertilization [4]. Also, pollinators can improve the distribution of pollen on the stigmatic surface of fertile flowers as well as promote cross-pollination [4], which is known to increase seed or fruit set in many crops.

Soybean Cultivation Needs Pollinator Management

In the previous section, we have compiled information showing that soybeans depend on pollinators for enhanced productivity. The scientific literature also points out that there are large pollinator deficits in soybean farms, which result from a mismatch between demand for, and supply of, pollination services (Table S1). On the one hand, a large soybean monoculture field has millions of pollen-sterile flowers needing pollinators to achieve pollination [4]. On the other hand, soybean cultivation typically occurs within large, monocultural fields that lack other types of habitats and use large amounts of pesticides; together, these factors greatly reduce the abundance and richness of pollinators [5]. Pollinator deficits were also found at the global level through a coordinated protocol across regions and crops on 344 fields from 33 pollinator-dependent crop systems (not including soybeans) by

showing that enhancing pollinator density and richness improved crop yields by an average of 24% [6]. This is especially important when considering that, although the honey bee seems to be the most abundant soybean pollinator and has proven to be effective for different varieties (Table S1), several studies reported wild insects pollinating soybean crops (Table S1), mainly other bees but also Diptera, Coleoptera, and Lepidoptera.

Harnessing the yield advantages of biotic pollination requires attention to the habitat needs of pollinators, as both wild and managed pollinators are needed for optimal pollination (Table S1) [7]. Conservation or restoration of native habitats near soybeans supports wild pollinators [8]. Establishing floral strips and hedgerows within and around soybean fields can promote wild pollinators [9,10] and improve honey bee health [11], but how much these practices increase soybean productivity is uncertain and arises as an important new area of research. Enhancing the nesting habitat for wild bees in soybean fields can also increase crop yield and requires only small changes to land use relative to the overall productivity gains [12]. For all of these habitat enhancements to be effective, pest management practices would need to be modified to promote pollinator management [5].

A recent study demonstrates that when the benefit to crop yield is on average 25%, around 20% of working land area can be allocated to native habitats without any loss in agricultural production [8]. Considering that soybeans cover 129 million hectares globally (<http://www.fao.org/faostat/en/#home>), this equates to 25.8 million hectares that could be restored as habitats for wild pollinators and other wildlife within agricultural working lands. Even if increases in soybean productivity due to integrating pollinator habitats are less than 25%, a restoration target of 20% of working land area can be maintained if lands with lower crop productivity are allocated to native habitats [8]. This simple exercise exemplifies the substantial potential for restoring native habitats within soybean landscapes. More detailed analyses considering the spatial distribution of soybean fields and existing native habitats (as well as better quantification of the level of pollinator deficit) should be performed to more precisely evaluate the amount and placement of land for restoration (see Figure 1 in [8] for an example on soybeans).

Other important benefits can be garnered by creating and maintaining pollinator habitats. For agricultural enterprises, these habitats can also help reduce soil degradation and loss through erosion, provide

source populations for biocontrol of pests, or be integrated within resistance management programs to prolong the effectiveness of pesticides [8–10]. For the society as a whole, these habitats can help improve water quality, flood control, and carbon sequestration [8]. Economic activities and job growth related to agriculture, including bee-keeping, but also restoration activities and agritourism are further supported [13]. By contrast, the expansion of soybean cultivation has been associated with the loss of on-farm jobs and migration of rural people to urban areas, where they largely remain poor and unemployed [2,13].

Improving soybean pollination can help curb the loss of natural forests, savannahs, and grasslands, but only if strong policies limit further soybean expansion. Policies to limit agricultural expansion are needed because of the potential for Jevon's paradox to occur, where an increase in production efficiency causes an expansion in markets (and thus, land in production) due to altered demand [14]. That is, if soybeans can be grown more efficiently, through enhanced pollination in this case, then new uses are likely to be found for this versatile product, which will in turn grow its market demand [14]. Due to its many uses (food, fodder, oil, and industrial), soybean is a classic example of the type of product whose markets could easily expand. Enhancing yields through pollination and making production cheaper could

actually cause more habitat conversion unless strong policies that restrict agricultural expansion are implemented.

Creating and maintaining pollinator habitats within soybean landscapes is a relatively unexplored production management option. Boosting yields within existing cropland could restore large areas of habitat without reducing yields, preventing further land degradation and biodiversity loss. Further benefits could flow to farms and society, including soil protection and regeneration, water and air purification, pest control, and new employment opportunities [8,13]. We urge the incorporation of pollinator science into soybean production, along with associated policies to restrict agricultural expansion into natural habitats.

Declaration of Interests

No interests are declared.

Supplemental Information

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